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Millward

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(54) **METHODS OF FORMING AN ARRAY OF OPENINGS IN A SUBSTRATE, AND RELATED METHODS OF FORMING A SEMICONDUCTOR DEVICE STRUCTURE**

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ABSTRACT

A method of forming an array of openings in a substrate. The method comprises forming a template structure comprising a plurality of parallel features and a plurality of additional parallel features perpendicularly intersecting the plurality of additional parallel features of the plurality over a substrate to define wells, each of the plurality of parallel features having substantially the same dimensions and relative spacing as each of the plurality of additional parallel features. A block copolymer material is formed in each of the wells. The block copolymer material is processed to form a patterned polymer material defining a pattern of openings. The pattern of openings is transferred to the substrate to form an array of openings in the substrate. A method of forming a semiconductor device structure, and a semiconductor device structure are also described.

(52) **U.S. Cl.**

CPC **H01L 21/0337** (2013.01); **H01L 21/76816** (2013.01); **H01L 27/10888** (2013.01)

(58) **Field of Classification Search**

USPC 257/622, E21.24, E21.259; 438/424, 438/780

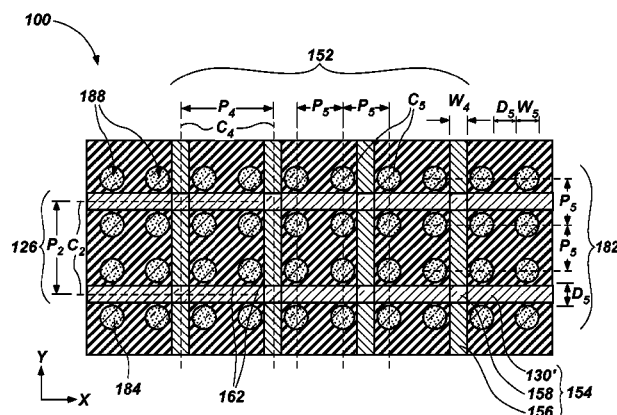
See application file for complete search history.

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21 Claims, 10 Drawing Sheets



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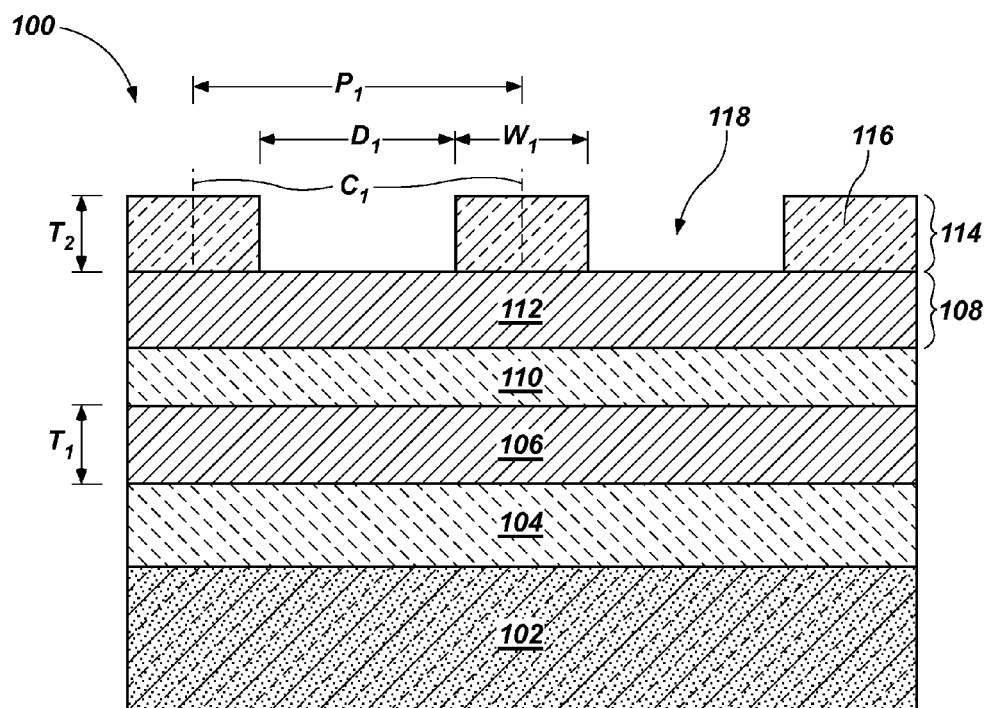


FIG. 1

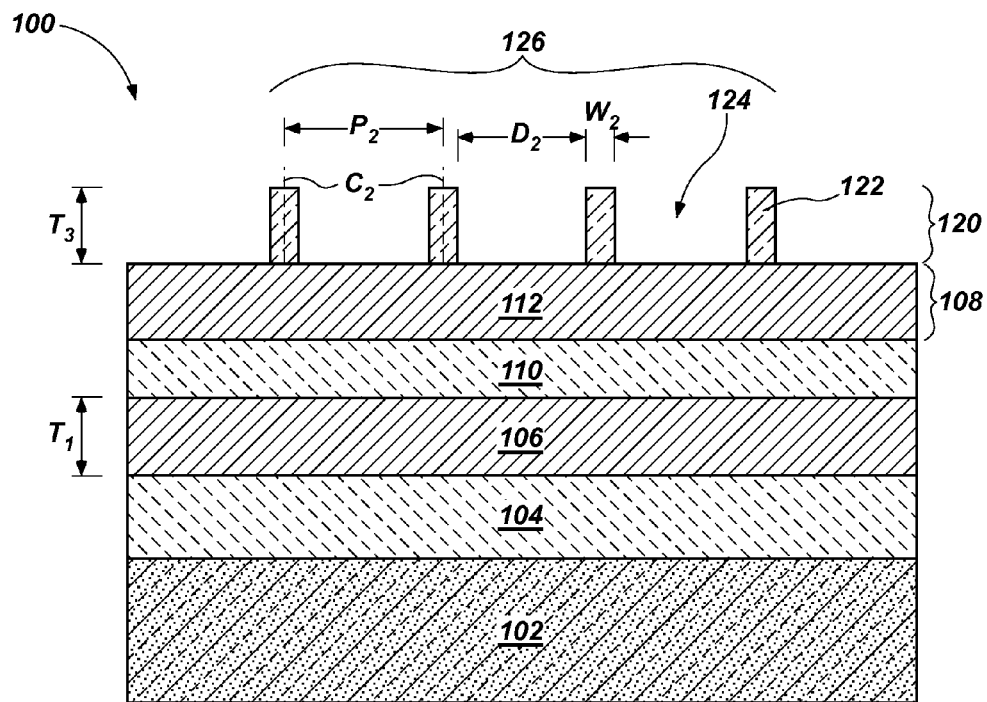


FIG. 2

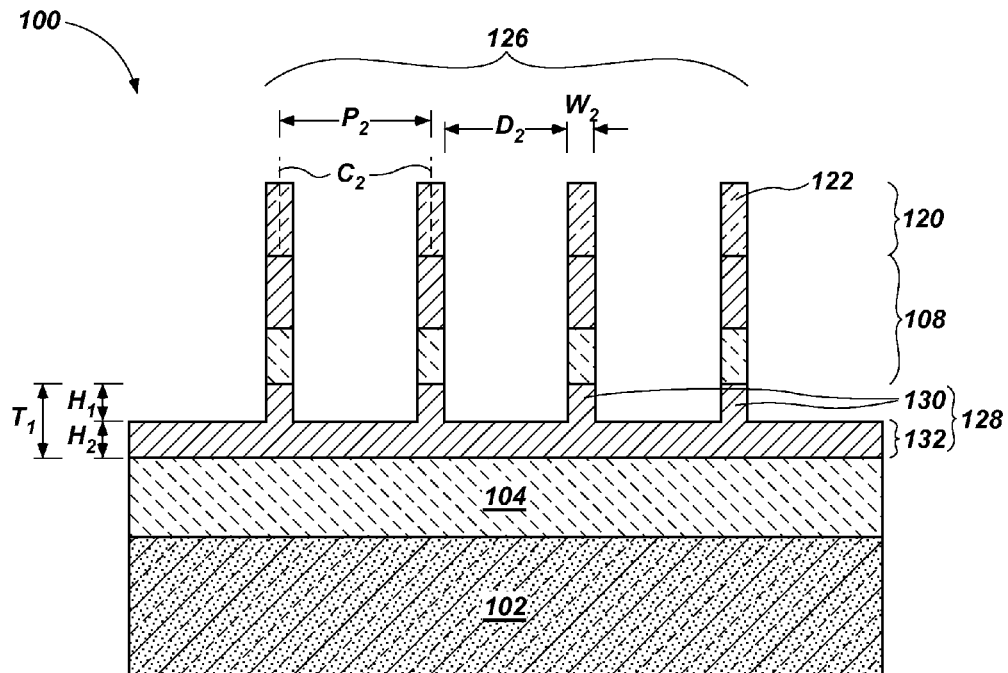


FIG. 3

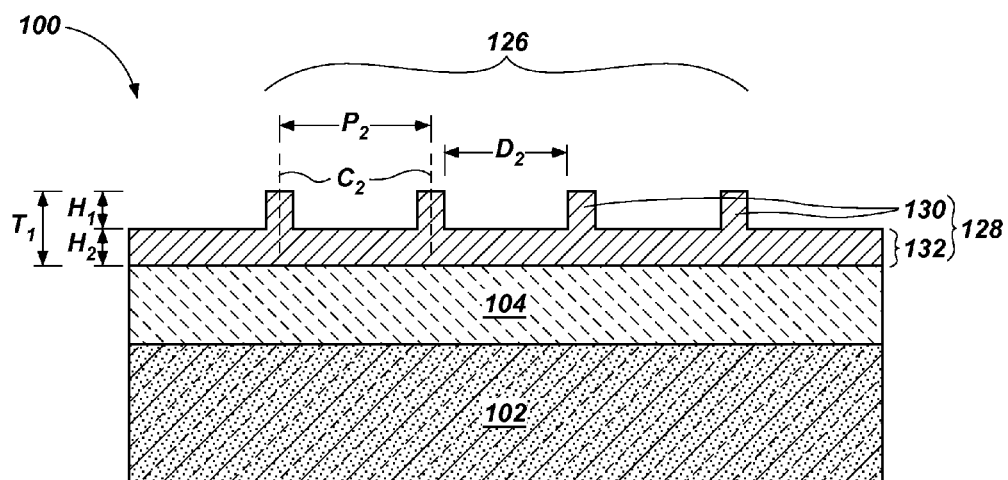


FIG. 4

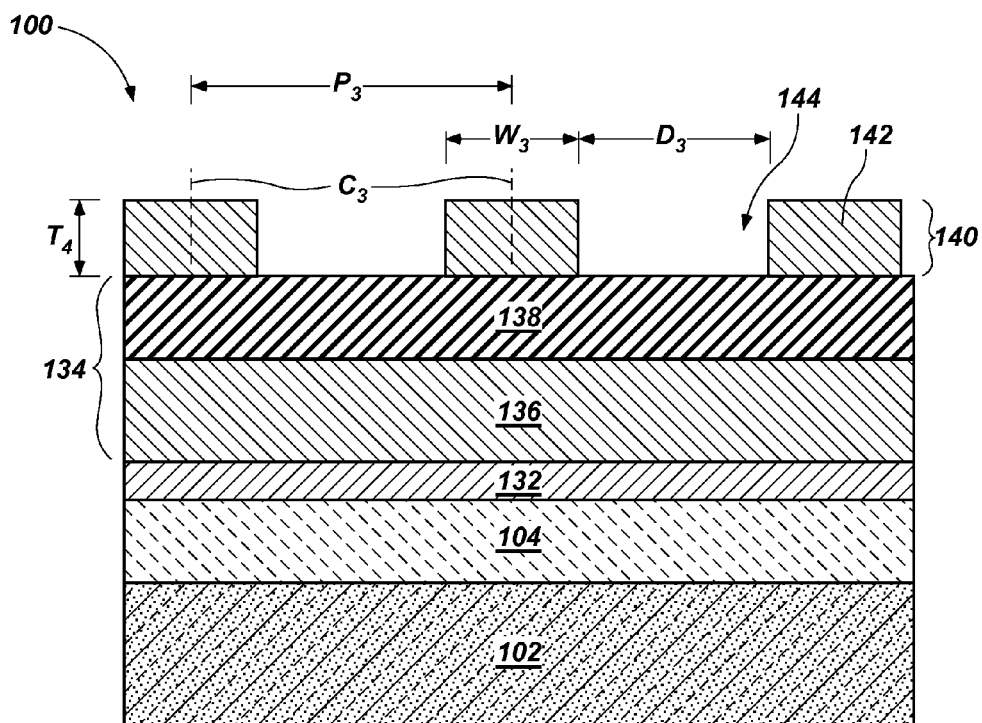


FIG. 5

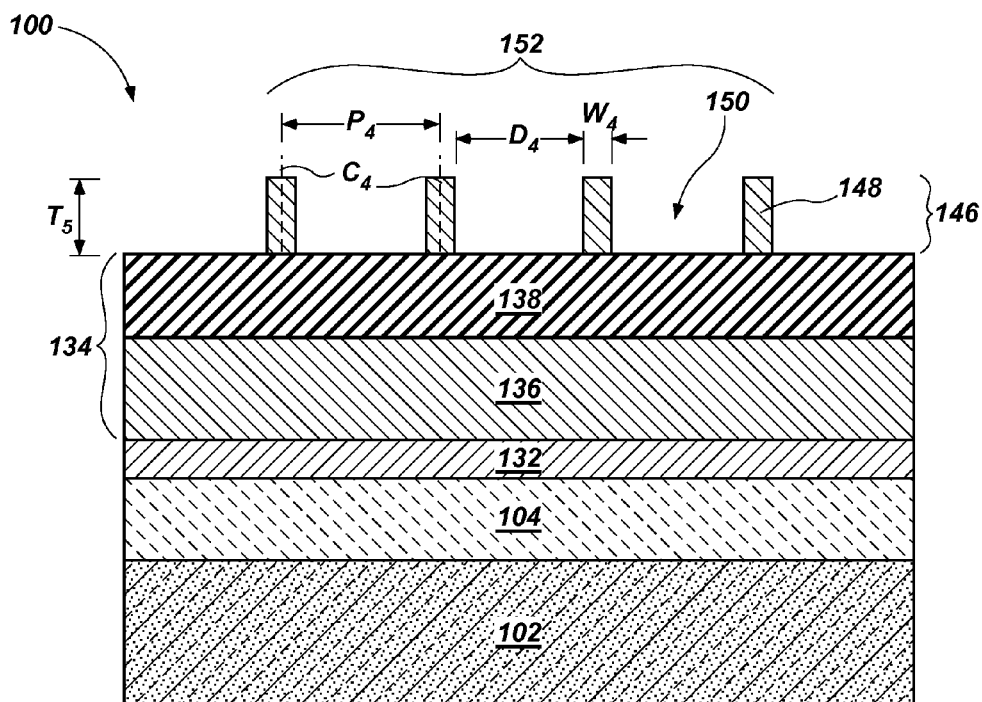


FIG. 6

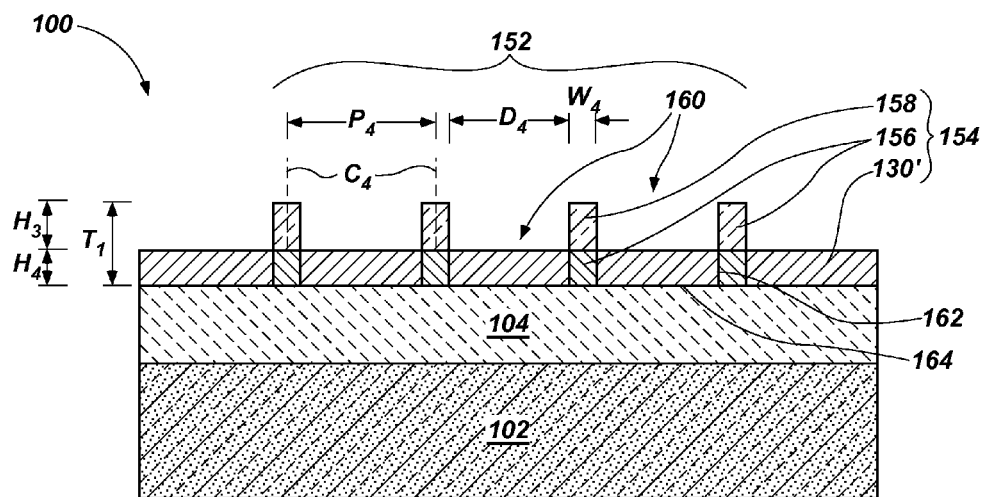


FIG. 7A

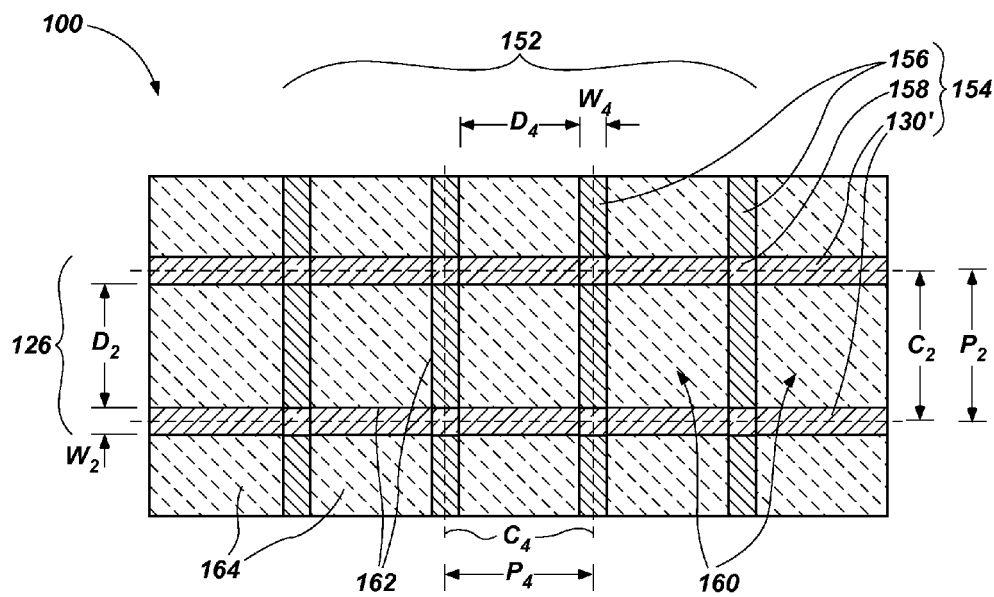


FIG. 7B

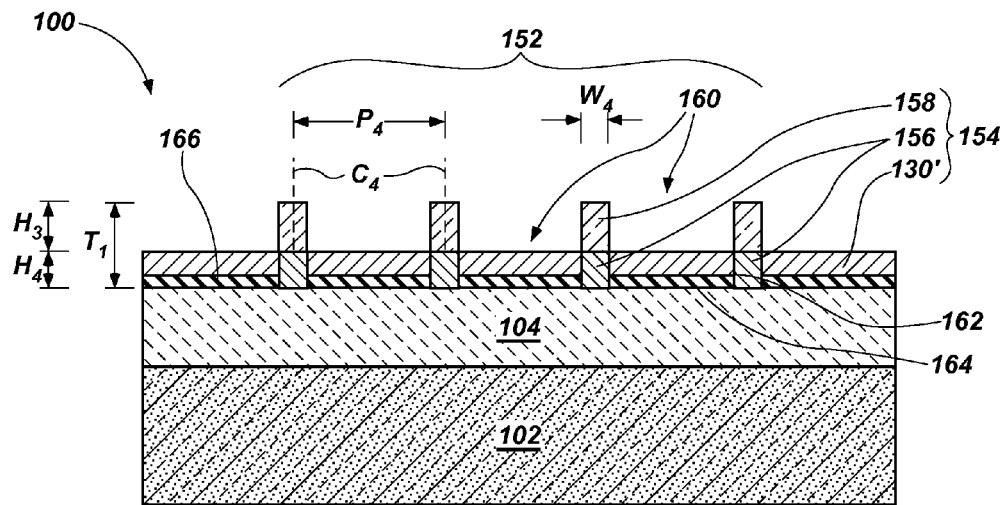


FIG. 8A

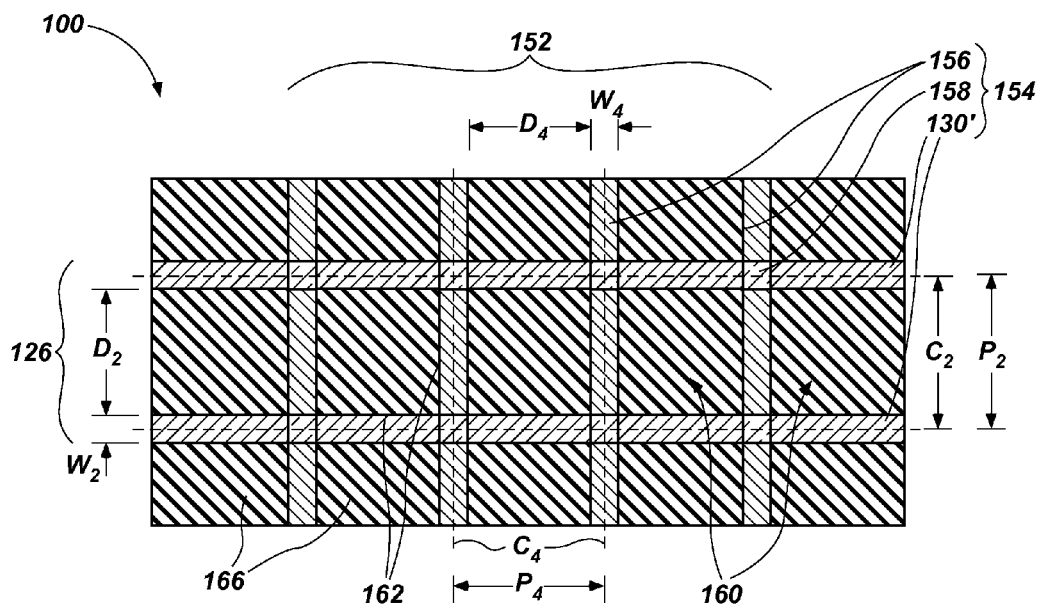


FIG. 8B

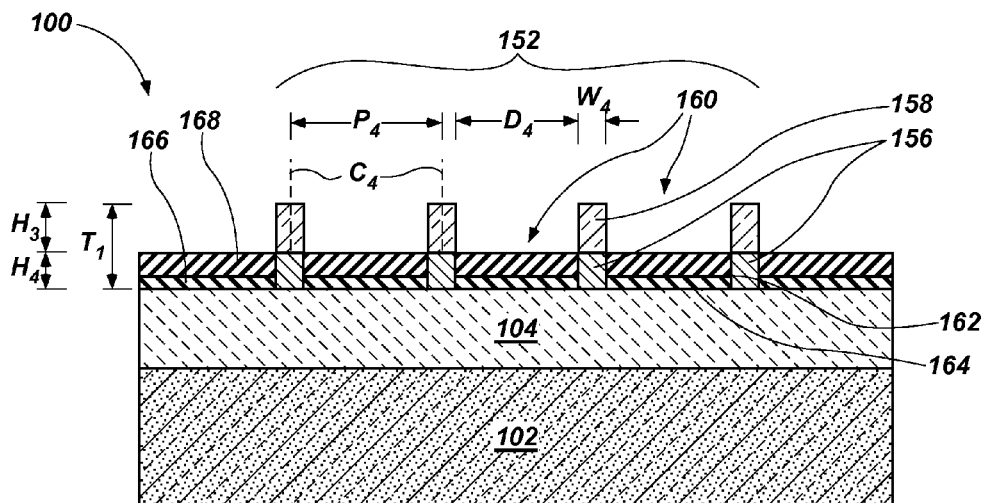


FIG. 9A

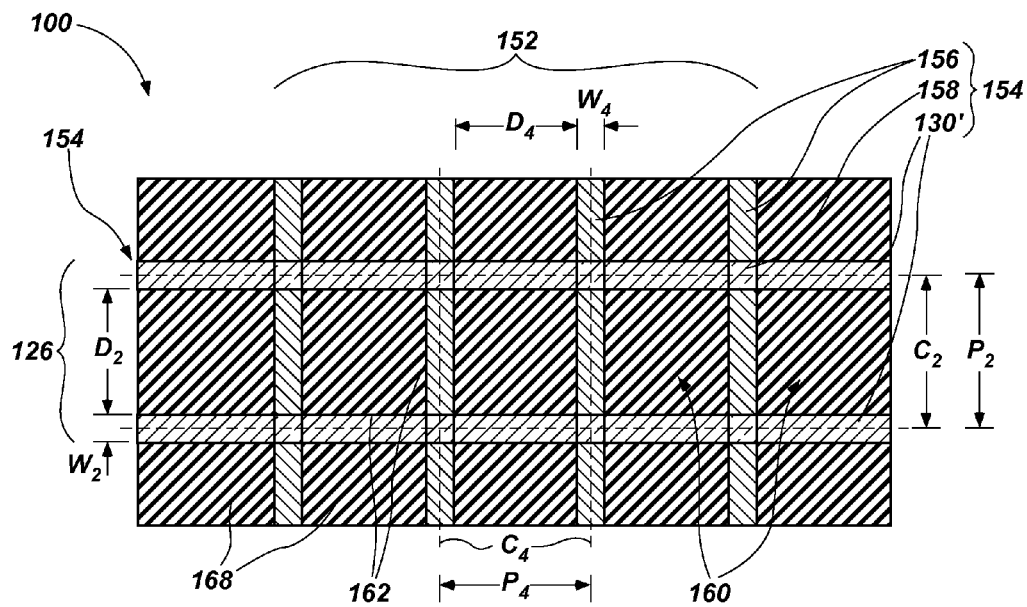
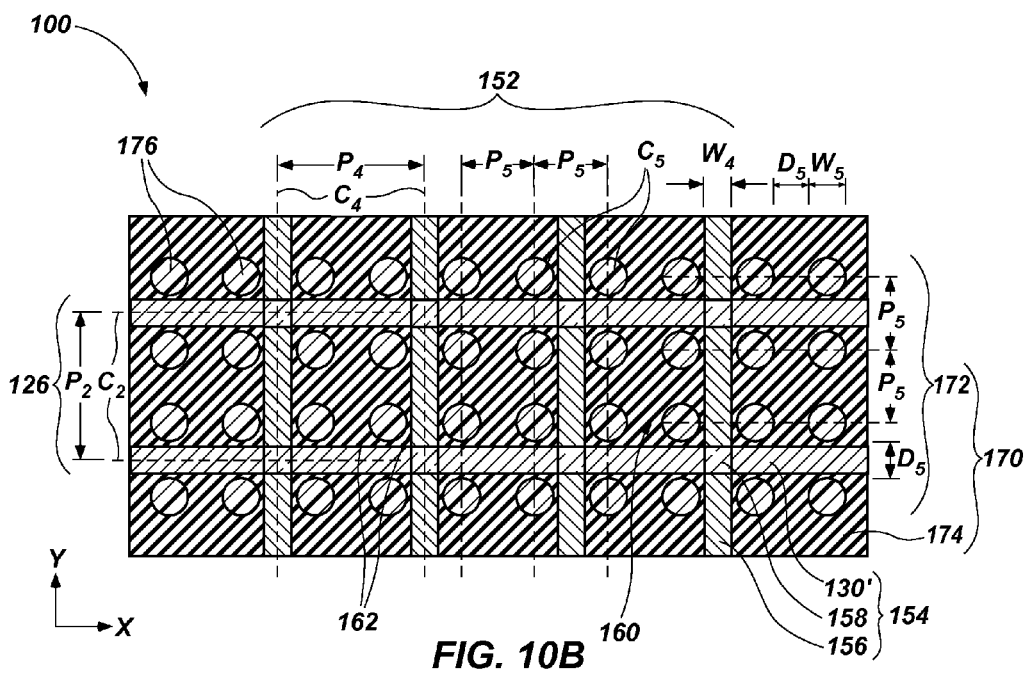


FIG. 9B



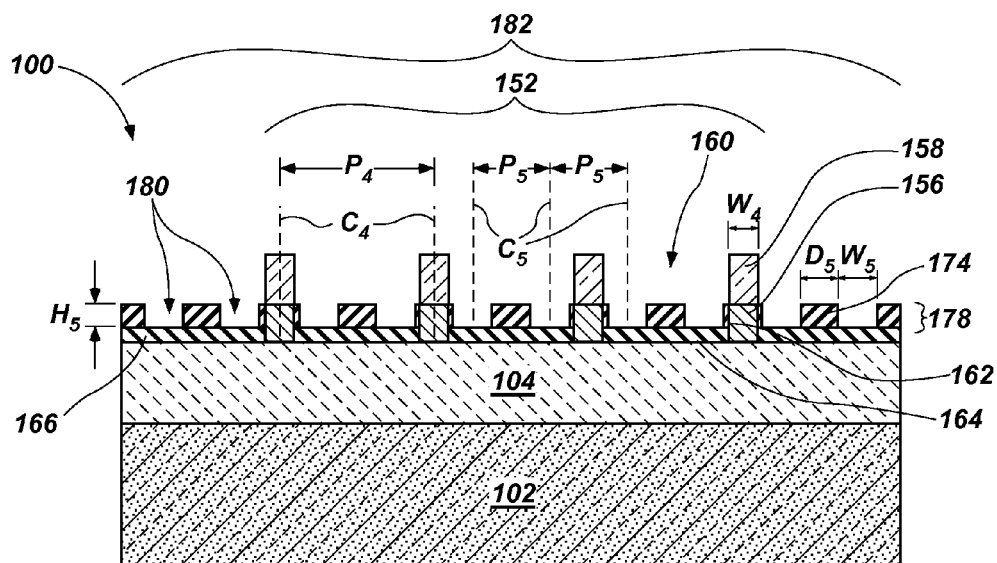
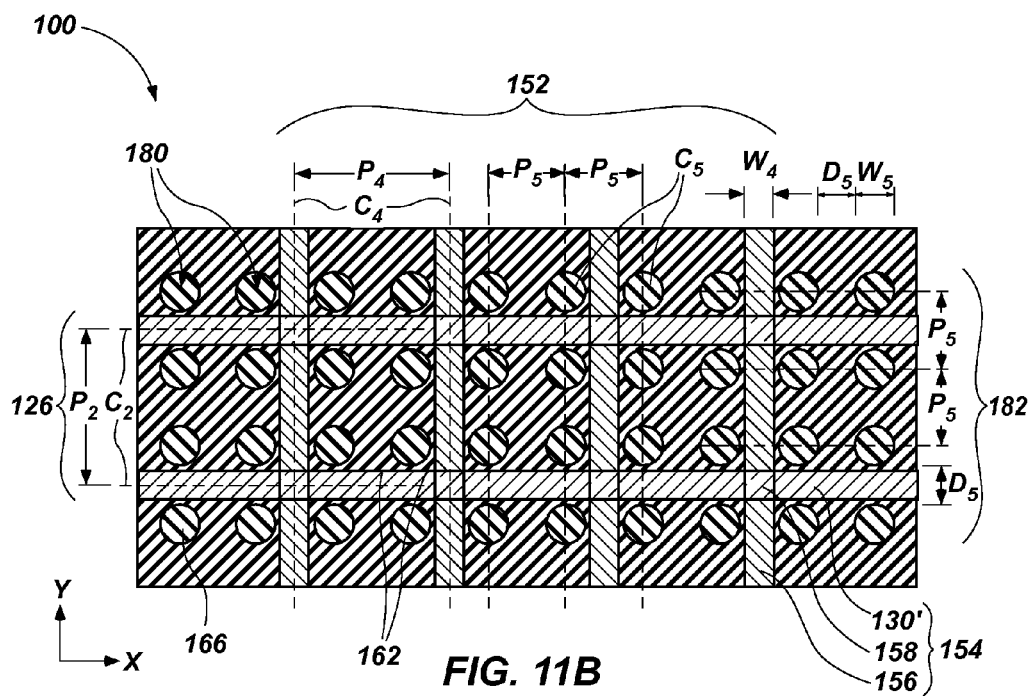


FIG. 11A



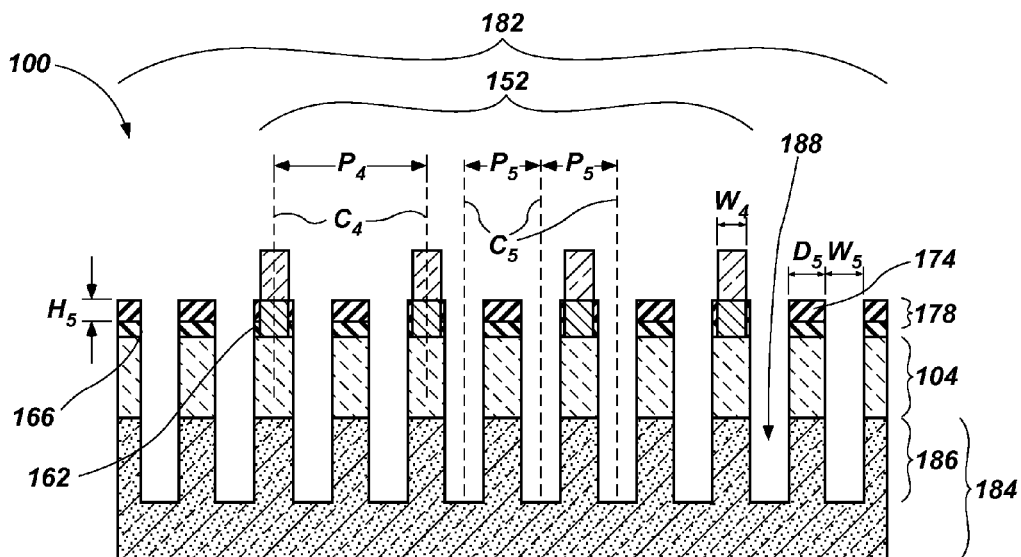


FIG. 12A

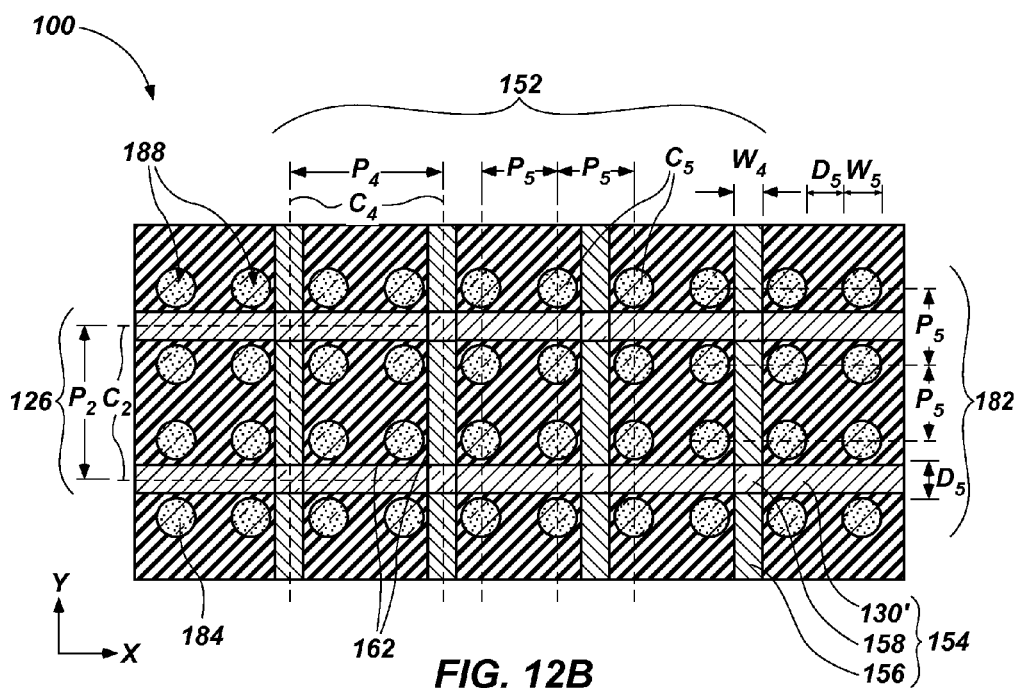


FIG. 12B

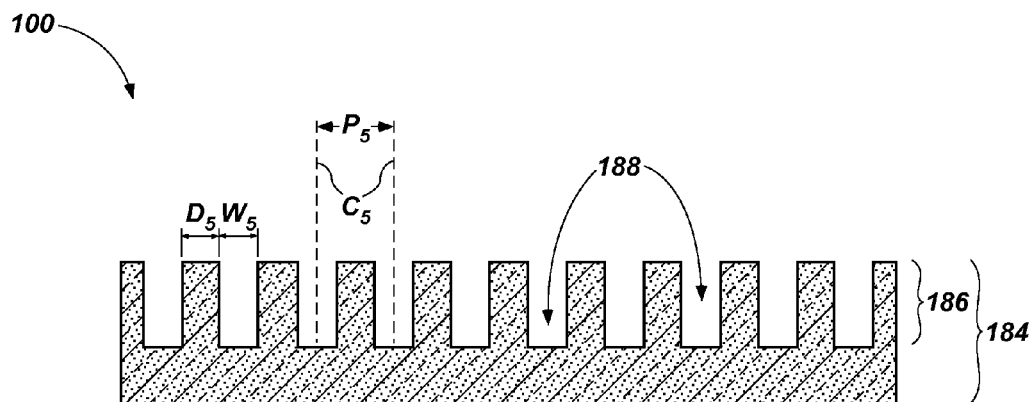


FIG. 13A

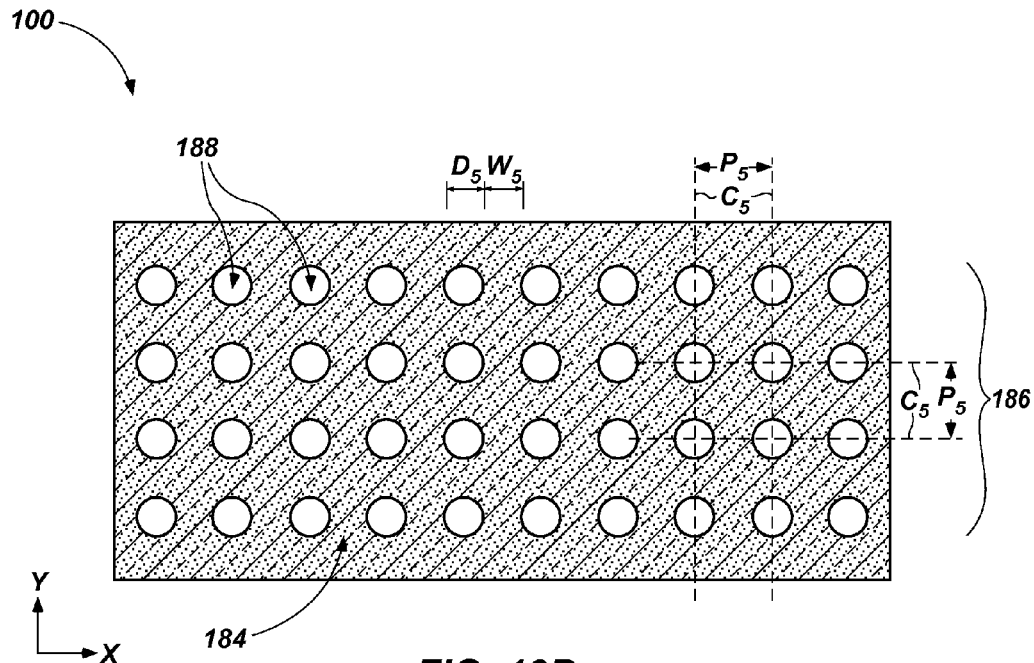


FIG. 13B

1

METHODS OF FORMING AN ARRAY OF OPENINGS IN A SUBSTRATE, AND RELATED METHODS OF FORMING A SEMICONDUCTOR DEVICE STRUCTURE

TECHNICAL FIELD

Embodiments of the disclosure relate to the field of semiconductor device design and fabrication. More specifically, embodiments of the disclosure relate to methods of forming an array of openings in a substrate, to related methods of forming a semiconductor device structure, and to a related semiconductor device structure.

BACKGROUND

A continuing goal of integrated circuit fabrication is to decrease the dimensions thereof. Integrated circuit dimensions can be decreased by reducing the dimensions and spacing of the constituent features or structures thereof. For example, by decreasing the dimensions and spacing of features (e.g., storage capacitors, access transistors, access lines, etc.) of a memory device, the overall dimensions of the memory device may be decreased while maintaining or increasing the storage capacity of the memory device.

Reducing the dimensions and spacing of semiconductor device features places ever increasing demands on the methods used to form the features. For example, due to limitations imposed by optics and radiation wavelengths, many conventional photolithographic methods cannot facilitate the formation of features having critical dimensions (e.g., widths, diameters, etc.) of less than about sixty (60) nanometers (nm). Electron beam (E-beam) lithography and extreme ultraviolet (EUV) lithography have been used to form features having critical dimensions less than 60 nm, but generally require complex processes and significant costs.

One approach for achieving features having critical dimensions of less than about 60 nm has been the use of pitch density multiplication processes, such as pitch density doubling processes. In a conventional pitch density doubling process, a photolithographic process is used to form photoresist lines over a sacrificial material over a substrate. The sacrificial material is etched using the photoresist lines to form mandrels, the photoresist lines are removed, spacers are formed on sides of the mandrels, and the mandrels are removed. The remaining spacers are used as a mask to pattern the substrate. Where the initial photolithography process formed one feature and one trench across a particular width of the substrate, after pitch density doubling, the same width of the substrate can include two smaller features and two smaller trenches, the width of each of the smaller trenches defined by the width of the spacers. Thus, the use of pitch density doubling can halve the minimum critical dimensions of features formed by the photolithographic processes, resulting in features having minimum critical dimension of about 30 nm. However, to achieve features having critical dimensions less than about 30 nm, the pitch density doubling process needs to be repeated (i.e., the process becomes a pitch density quadrupling process), significantly increasing processing time as well as energy and material costs.

Another approach for achieving semiconductor device features having critical dimensions of less than about 60 nm has been the use of self-assembling (SA) block copolymers. For example, an SA block copolymer deposited within a trench having particular graphoepitaxial characteristics (e.g., dimensions, wetting properties, etc.) may be annealed to form select morphology (e.g., spherical, lamellar, cylindrical, etc.)

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domains of one polymer block of the SA block copolymer within a matrix domain of another polymer block of the SA block copolymer. The select morphology domains or the matrix domain can be selectively removed, and the remaining select morphology domains or matrix domain utilized as an etch mask for patterning features into an underlying substrate. As the dimensions of the select morphology domains and the matrix domain are at least partially determined by the chain length of the SA block copolymer, feature dimensions much smaller than 60 nm are achievable (e.g., dimensions similar to those achievable through E-beam and EUV lithography processes). Such methods have, for example, been used to form close-packed, hexagonal arrays of openings in an underlying substrate. However, certain semiconductor device structures may utilize different (i.e., non-hexagonal) array configurations. For example, Dynamic Random Access Memory (DRAM) device structures may utilize rectilinear arrays of openings (e.g., contact openings) rather than hexagonal arrays of openings.

A need, therefore, exists for new, simple, and cost-efficient methods of forming a rectilinear array of openings for a semiconductor device structure, such as, for example, a rectilinear contact array for a memory device structure, that enables the formation of the closely packed openings having critical dimensions (e.g., widths, diameters, etc.) less than or equal to about 30 nm.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

FIGS. 1 through 13B are cross-sectional (i.e., FIGS. 1 through 7A, 8A, 9A, 10A, 11A, 12A, and 13A) and top-down (FIGS. 7B, 8B, 9B, 10B, 11B, 12B, and 13B) views of a semiconductor device structure in accordance with embodiments of the disclosure, and illustrate a method of forming a rectilinear array of openings in a substrate of a semiconductor device structure, in accordance with embodiments of the disclosure.

DETAILED DESCRIPTION

Methods of forming a rectilinear array of openings (e.g., a rectilinear contact array) in a substrate are disclosed, as are related methods of forming a semiconductor device structure including the rectilinear array of openings, and a related semiconductor device structure including the rectilinear array of openings. In some embodiments, a template structure having the dimensions, spacing, and wetting characteristics for forming a rectilinear array of cylindrical domains of a first polymer within a matrix domain of a second polymer from a block copolymer material may be formed over a substrate by way of pitch density doubling processes. An appropriate block copolymer material may be deposited in wells defined by the template structure, the block polymer material may be processed (e.g., annealed) to form a self-assembled block copolymer material, and the cylindrical domains of the first polymer may be selectively removed to form a patterned polymer material. The patterned polymer material may be used as a mask to form a rectilinear array of openings in the substrate. The openings of the rectilinear array may each have substantially the same width, such as less than or equal to about 30 nm, and a pitch between adjacent openings may be substantially uniform, such as less than or equal to about 50 nm. The rectilinear array of openings may, for example, be utilized in a dynamic random access memory (DRAM) device. The methods of forming the rectilinear array of openings disclosed herein may decrease processing complexity,

steps, and cost relative to conventional methods of forming a rectilinear array of openings. The methods of the disclosure may enable increased opening density, facilitating increased performance in semiconductor device structures (e.g., DRAM cells) and semiconductor devices (e.g., DRAM devices) that rely on high opening (e.g., contact) density.

As used herein, the term “rectilinear array” means and includes an array including rows of features that intersect columns of features at about a ninety degree (90°) angle. Accordingly, a “rectilinear array of openings” means and includes an array of openings including rows of openings that intersect columns of openings at about a ninety degree (90°) angle.

As used herein, the term “pitch” refers to the distance between identical points in two adjacent (i.e., neighboring) features. By way of non-limiting example, the pitch between two adjacent cylindrical domains may be viewed as the sum of the radii of the adjacent cylindrical domains and any space between the adjacent cylindrical domains. Stated another way, the pitch in the foregoing example may be characterized as the distance between the centers of the adjacent cylindrical domains.

As used herein, relational terms, such as “first,” “second,” “over,” “top,” “bottom,” “underlying,” etc., are used for clarity and convenience in understanding the disclosure and accompanying drawings and does not connote or depend on any specific preference, orientation, or order, except where the context clearly indicates otherwise.

As used herein, the term “substantially,” in reference to a given parameter, property, or condition, means to a degree that one of ordinary skill in the art would understand that the given parameter, property, or condition is met with a small degree of variance, such as within acceptable manufacturing tolerances.

The following description provides specific details, such as material types, material thicknesses, and processing conditions in order to provide a thorough description of embodiments of the disclosure. However, a person of ordinary skill in the art will understand that the embodiments of the present disclosure may be practiced without employing these specific details. Indeed, the embodiments of the present disclosure may be practiced in conjunction with conventional fabrication techniques employed in the industry. In addition, the description provided below does not form a complete process flow for manufacturing a semiconductor device. The semiconductor device structures described below do not form a complete semiconductor device. Only those process acts and structures necessary to understand the embodiments of the disclosure are described in detail below. Additional acts to form the complete semiconductor device from the semiconductor device structures may be performed by conventional fabrication techniques. Also note, any drawings accompanying the present application are for illustrative purposes only, and are thus not drawn to scale. Additionally, elements common between figures may retain the same numerical designation.

FIGS. 1 through 13B, are simplified cross-sectional (i.e., FIGS. 1 through 7A, 8A, 9A, 10A, 11A, 12A, and 13A) and top-down (i.e., FIGS. 7B, 8B, 9B, 10B, 11B, 12B, and 13B) views illustrating embodiments of a method of forming a rectilinear array of openings in a substrate of a semiconductor device structure, such as a rectilinear contact array for a DRAM device structure. With the description provided below, it will be readily apparent to one of ordinary skill in the art that the methods described herein may be used in various

devices. In other words, the methods of the disclosure may be used whenever it is desired to form a rectilinear array of openings in a substrate.

Referring to FIG. 1, a semiconductor device structure **100** may include a substrate **102**, a substrate masking material **104** over the substrate **102**, a template material **106** over the substrate masking material **104**, template masking materials **108** over the template material **106**, and a patterned photoresist material **114** over the template masking materials **108**. As used herein, the term “substrate” means and includes a base material or other construction upon which additional materials are formed. The substrate **102** may be a semiconductor substrate, a base semiconductor layer on a supporting structure, a metal electrode or a semiconductor substrate having one or more layers, structures or regions formed thereon. The substrate **102** may be a conventional silicon substrate or other bulk substrate comprising a layer of semiconductive material. As used herein, the term “bulk substrate” means and includes not only silicon wafers, but also silicon-on-insulator (SOI) substrates, such as silicon-on-sapphire (SOS) substrates and silicon-on-glass (SOG) substrates, epitaxial layers of silicon on a base semiconductor foundation, and other semiconductor or optoelectronic materials, such as silicon-germanium, germanium, gallium arsenide, gallium nitride, and indium phosphide. The substrate **102** may be doped or undoped.

The substrate masking material **104** may be a material that is selectively etchable relative to a domain of a self-assembled block copolymer material to be formed over the substrate masking material **104**, as described in further detail below. As used herein, a material is “selectively etchable” relative to another material if the material exhibits an etch rate that is at least about five times (5×) greater than the etch rate of another material, such as about ten times (10×) greater, about twenty times (20×) greater, or about forty times (40×) greater. The substrate **102** may be selectively etchable relative to the substrate masking material **104**. In some embodiments, the substrate masking material **104** is formed of and includes amorphous carbon. A thickness of the substrate masking material **104** may be selected at least partially based on the etch chemistries and process conditions used to form the rectilinear array of openings of the disclosure, as described in further detail below. By way of non-limiting example, the substrate masking material **104** may have a thickness within a range of from about 100 nanometers (nm) to about 1000 nm, such as from about 200 nm to about 800 nm, or from about 300 nm to about 700 nm. In some embodiments, the substrate masking material **104** has a thickness of about 600 nm.

The template material **106** may be a material that, upon being patterned, facilitates forming a self-assembled block copolymer material including a rectilinear array of cylindrical domains of a first polymer within a matrix domain of a second polymer, as described in further detail below. The template material **106** may, for example, be a material that is preferential wetting to a polymer block (e.g., a minority block, or a majority block) of the block copolymer material (as well as any homopolymers included in the block copolymer material that are of the same polymer type as the polymer block). As a non-limiting example, template material **106** may be formed of and include at least one of a silicon oxide, a silicon nitride, a silicon oxycarbide, and a dielectric anti-reflective coating (DARC) (e.g., a silicon oxynitride, such as a silicon-rich silicon oxynitride). In some embodiments, the template material **106** is selected to be preferential wetting toward a polymethylmethacrylate (PMMA) block of poly (styrene-*b*-methylmethacrylate) (PS-*b*-PMMA). In additional embodiments, the template material **106** is selected to be preferential wetting toward a polydimethylsiloxane

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(PDMS) block of poly(styrene-block-dimethylsiloxane) (PS-b-PDMS). The template material **106** may have a thickness T_1 conducive to the patterning of the template material **106** to form a template structure, as described in further detail below. By way of non-limiting example, the thickness T_1 of the template material **106** may be within a range of from about 50 nanometers (nm) to about 500 nm, such as from about 50 nm to about 100 nm. In some embodiments, the thickness T_1 of the template material **106** is about 75 nm.

The template masking materials **108** may include materials that aid in the patterning of the template material **106**. For example, as depicted in FIG. 1, the template masking materials **108** may include a protective material **110** over the template material **106** and a hard mask material **112** over the protective material **110**. Each of the protective material **110** and the hard mask material **112** may be selectively etchable relative to spacers to be formed over the template masking materials **108**. The protective material **110** and the hard mask material **112** may be the same as or different than the substrate masking material **104** and the template material **106**, respectively. By way of non-limiting example, the protective material **110** may be formed of and include amorphous carbon, and the hard mask material **112** may be formed of and include at least one of silicon, a silicon oxide, a silicon nitride, a silicon oxycarbide, aluminum oxide, and a silicon oxynitride. The protective material **110** may have a thickness within a range of from about 50 nm to about 300 nm, such as from about 60 nm to about 200 nm. The hard mask material **112** may have a thickness within a range of from about 10 nm to about 50 nm, such as from about 10 nm to about 40 nm. In some embodiments, the protective material **110** has a thickness of about 70 nm, and the hard mask material **112** has a thickness of about 26 nm. In embodiments where the template material **106** is selectively etchable relative to a spacer material to be formed thereover, at least a portion of the template masking materials **108** (e.g., at least one of the protective material **110** and the hard mask material **112**) may, optionally, be omitted.

Each of the substrate **102**, the substrate masking material **104**, the template material **106**, and the template masking materials **108** (if present) may be formed using conventional processes including, but not limited to, physical vapor deposition ("PVD"), chemical vapor deposition ("CVD"), atomic layer deposition ("ALD"), or spin-coating. PVD includes, but is not limited to, sputtering, evaporation, or ionized PVD. Such processes are known in the art and, therefore, are not described in detail herein.

The patterned photoresist material **114** may include parallel photoresist lines **116** separated by first trenches **118**. As used herein, the term "parallel" means substantially parallel. Each of the parallel photoresist lines **116** may be formed of and include a conventional photoresist, such as a photoresist compatible with 13.7 nm, 157 nm, 193 nm, 248 nm, or 365 nm wavelength systems, a photoresist compatible with 193 nm wavelength immersion systems, or a photoresist compatible with electron beam lithographic systems. By way of non-limiting example, each of the parallel photoresist lines **116** may be formed of and include an argon fluoride (ArF) sensitive photoresist (i.e., a photoresist suitable for use with an ArF light source), or a krypton fluoride (KrF) sensitive photoresist (i.e., a photoresist suitable for use with a KrF light source).

Each of the parallel photoresist lines **116** may have substantially the same width W_1 , thickness T_2 , and length (not shown). In addition, the parallel photoresist lines **116** may be regularly spaced by a distance D_1 (i.e., the width of each of the first trenches **118**). Accordingly, a pitch P_1 between centerlines C_1 of adjacent parallel photoresist lines may be substantially uniform throughout the patterned photoresist material

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114. The dimensions and spacing of the parallel photoresist lines **116** may be selected to provide desired dimensions and spacing to parallel spacers to be formed on the parallel photoresist lines **116**. For example, the width W_1 and the centerline C_1 location of each of the parallel photoresist lines **116** may be selected to facilitate the formation of parallel spacers exhibiting smaller dimensions and decreased pitch relative to the parallel photoresist lines **116**, as described in further detail below. In some embodiments, the width W_1 of each of the parallel photoresist lines **116** is about 50 nm, the distance D_1 between adjacent parallel photoresist lines is about 70 nm, and the pitch P_1 between adjacent parallel photoresist lines is about 120 nm.

The patterned photoresist material **114** may be formed using conventional processing techniques, which are not described in detail herein. By way of non-limiting example, a photoresist material (not shown) may be formed over the template masking materials **108** and exposed to an appropriate wavelength of radiation through a reticle (not shown) and then developed. The parallel photoresist lines **116** may correlate to portions of the photoresist material remaining after the development, and the first trenches **118** may correlate to portions of the photoresist material removed during the development.

Referring to next to FIG. 2, the patterned photoresist material **114** (FIG. 1) may be used to form a patterned spacer material **120** including parallel spacers **122** separated by second trenches **124**. The patterned spacer material **120** may define a first pattern **126** to be transferred to the template material **106**, as described in further detail below. Each of the parallel spacers **122** may be formed of and include a material suitable for use as a mask for selectively removing (e.g., etching) of portions of the template masking materials **108** and the template material **106**. By way of non-limiting example, each of the parallel spacers **122** may be formed of and include a silicon oxide or a silicon nitride. In some embodiments, each of the parallel spacers **122** is formed of and includes a silicon oxide.

Each of the parallel spacers **122** may have substantially the same width W_2 , thickness T_3 , and length (not shown). The thickness T_3 of each of the parallel spacers **122** may be substantially the same as the thickness T_2 of each of the parallel photoresist lines **116** (FIG. 1). In addition, the parallel spacers **122** may be oriented parallel to one another, and may be regularly spaced by a distance D_2 (i.e., the width of each of the second trenches **124**) that is substantially the same as the width W_1 of each of the parallel photoresist lines **116**. A pitch P_2 between centerlines C_2 of adjacent parallel spacers may be equal to about half of the pitch P_1 between the centerlines C_1 of adjacent photoresist lines of the patterned photoresist material **114** (FIG. 1). The dimensions and spacing of the parallel spacers **122** may be selected to provide desired dimensions and spacing for features of a template structure to be formed using the patterned spacer material **120**, as described in further detail below. The width W_2 of each of the parallel spacers **122** may be within a range of from about 20 percent to about 40 percent of a target (e.g., desired) pitch between adjacent openings of a rectilinear array of openings to be formed using the template structure, such as from about 20 percent to about 30 percent of the target pitch. The distance D_2 between each of the parallel spacers **122** may be within a range of from about 180 percent to about 160 percent of the target pitch between adjacent openings of the rectilinear array of openings to be formed, such as from about 180 percent to about 170 percent of the target pitch. The pitch P_2 between adjacent parallel spacers of the patterned spacer material **120**

may be about two times ($2\times$) the target pitch between adjacent openings of the rectilinear array of openings to be formed.

By way of non-limiting example, if a target pitch between adjacent openings of the rectilinear array of openings to be formed is about 30 nm, the width W_2 of each of the parallel spacers **122** may be within a range of from about 6 nm to about 12 nm, the distance D_2 between adjacent parallel spacers of the patterned spacer material **120** may be within a range of from about 54 nm and about 48 nm, and the pitch P_2 between centerlines C_2 of adjacent parallel spacers of the patterned spacer material **120** may be about 60 nm. In some embodiments, the width W_2 of each of the parallel spacers **122** is about 10 nm, the distance D_2 between adjacent parallel spacers of the patterned spacer material **120** is about 50 nm, and the pitch P_2 between adjacent parallel spacers of the patterned spacer material **120** is about 60 nm.

A pitch density doubling process may be utilized to form the patterned spacer material **120** using the patterned photoresist material **114**. For example, referring collectively to FIGS. **1** and **2**, a spacer material (not shown) may be conformally formed (e.g., deposited using a PVD process, a CVD process, an ALD process, or a spin-coating process) over exposed surfaces of the parallel photoresist lines **116** and the template masking materials **108**. A thickness of the spacer material may correspond to the width W_2 of the parallel spacers **122** to be formed. An anisotropic etching process may be performed to remove the spacer material from horizontal surfaces of the parallel photoresist lines **116** and the template masking materials **108**, while maintaining the spacer material on vertical surfaces of the parallel photoresist lines **116**. As used herein, each of the terms "horizontal" and "lateral" means and includes extending in a direction substantially parallel to the substrate **102**, regardless of the orientation of the substrate **102**. Accordingly, as used herein, each of the terms "vertical" and "longitudinal" means and includes extending in a direction substantially perpendicular to the substrate **102**, regardless of the orientation of the substrate **102**. The parallel photoresist lines **116** may then be removed (e.g., etched, such as dry etched with a silicon-dioxide-containing plasma), resulting in the patterned spacer material **120**.

In additional embodiments, the patterned spacer material **120** may be formed using structures other than the parallel photoresist lines **116** of the patterned photoresist material **114**. Such structures may, for example, be utilized if forming the spacer material over exposed surfaces of the parallel photoresist lines **116** would damage or degrade (e.g., thermally degrade) the parallel photoresist lines **116**. By way of non-limiting example, a pattern defined by the patterned photoresist material **114** may be transferred (e.g., by way of at least one etching process) to the template masking materials **108** to form a patterned template masking material (not shown). The patterned spacer material **120** may then be formed using the patterned template masking material through a process substantially similar to that described above in relation to forming the patterned spacer material **120** using the patterned photoresist material **114**.

Referring to FIG. **3**, the first pattern **126** defined by the patterned spacer material **120** may be transferred or extended into the template material **106** (FIG. **2**) to form an intermediate template structure **128** including parallel features **130** protruding from a base **132**. The parallel features **130** may have substantially the same width W_2 , length (not shown), and pitch P_2 as each of the parallel spacers **122**. A height H_1 of each of the parallel features **130** may be within a range of from about 55 percent to about 45 percent of the thickness T_1 of the template material **106**. A height H_2 of the base **132** may

be equal to the difference between the height H_1 of each of the parallel features **130** and the thickness T_1 of the template material **106**. In some embodiments, the width W_2 of each of the parallel features **130** is about 10 nm, the pitch P_2 between adjacent parallel features is about 60 nm, the height H_1 of each of the parallel features **130** is about 35 nm, and the height H_2 of the base **132** is about 40 nm.

To form the intermediate template structure **128**, the parallel spacers **122** of the patterned spacer material **120** may be used as a mask for at least one etching process (e.g., an anisotropic etching process) to substantially remove unmasked portions (i.e., portions not underlying the parallel spacers **122**) of each of the template masking materials **108** and the template material **106**. The unmasked portions of the template masking materials **108** may be completely removed, and the unmasked portions of the template material **106** may be partially removed. The etching process may, for example, extend the first pattern **126** from about 45 percent to about 55 percent of the way through the template material **106**. As a non-limiting example, if the thickness T_1 of the template material **106** is about 75 nm, the first pattern **126** may be extended from about 35 nm to about 40 nm into the template material **106**.

Following the formation of the intermediate template structure **128**, remaining portions of the parallel spacers **122** and the template masking materials **108** may be removed, as depicted in FIG. **4**. The remaining portions of the parallel spacers **122** and the template masking materials **108** may be removed using conventional processes, such as conventional etching processes, which are not described in detail herein.

Referring to FIG. **5**, which illustrates a cross-sectional view of the semiconductor device structure **100** taken from a viewpoint approximately 90 degrees clockwise of that of FIGS. **1** through **4**, additional template masking materials **134** may be formed over the intermediate template structure **128**, and another patterned photoresist material **140** may be formed over the additional template masking materials **134**. In FIG. **5**, the base **132** of the intermediate template structure **128** is shown, but the parallel features **130** are not illustrated because they are covered by the additional template masking materials **134**. The additional template masking materials **134** may include materials that aid in further patterning the intermediate template structure **128** (FIG. **4**). For example, the additional template masking materials **134** may include an additional protective material **136** over the intermediate template structure **128**, and an additional hard mask material **138** over the additional protective material **136**. Each of the additional protective material **136** and the additional hard mask material **138** may be selectively etchable relative to additional parallel spacers to be formed over the additional template masking materials **134**. The additional protective material **136** and the additional hard mask material **138** may be the same as or different than the protective material **110** and the hard mask material **112** previously described with reference to FIG. **1**, respectively. By way of non-limiting example, the additional protective material **136** may be formed of and include amorphous carbon, and the additional hard mask material **138** may be formed of and include at least one of silicon, a silicon oxide, a silicon nitride, a silicon oxycarbide, aluminum oxide, and a silicon oxynitride.

The additional protective material **136** may have a thickness sufficient to cover and surround each of the parallel features **130** (FIG. **4**) of the intermediate template structure **128**, such as a thickness within a range of from about 40 nm to about 80 nm, or from about 50 nm to about 60 nm. The additional hard mask material **138** may have a thickness within a range of from about 10 nm to about 50 nm, such as

from about 10 nm to about 40 nm. In some embodiments, the additional hard mask material **138** has a thickness of about 80 nm, and the additional hard mask material **138** has a thickness of about 26 nm. In embodiments where the intermediate template structure **128** is selectively etchable relative to an additional spacer material to be formed thereover, at least a portion of the additional template masking materials **134** (e.g., the additional hard mask material **138**) may, optionally, be omitted. The additional template masking materials **134** may be formed using conventional processes (e.g., CVD, PVD, ALD, or spin-coating), which are not described in detail herein.

The another patterned photoresist material **140** may include additional parallel photoresist lines **142** separated by third trenches **144**. The additional parallel photoresist lines **142** may be formed of and include a conventional photoresist (e.g., an ArF sensitive photoresist, a KrF sensitive photoresist, etc.) that is the same as or different than that of the parallel photoresist lines **116** of the patterned photoresist material **114**, previously described with respect to FIG. 1. The additional parallel photoresist lines **142** may have substantially similar dimensions and spacing as the parallel photoresist lines **116**, except oriented in a direction substantially perpendicular to that of the parallel features **130** (FIG. 4) of the intermediate template structure **128** (i.e., perpendicular to the direction of the parallel photoresist lines **116**). For example, each of the additional parallel photoresist lines **142** may have a width W_3 , thickness T_4 , and length (not shown) substantially the same as the width W_1 , the thickness T_2 , and the length (not shown) of the parallel photoresist lines **116**, respectively. In additional embodiments, at least one of the thickness T_4 and the length of each of the additional parallel photoresist lines **142** may be different than at least one of the thickness T_2 and the length of the parallel photoresist lines **116**. The additional parallel photoresist lines **142** may be regularly spaced by a distance D_3 that is substantially the same as the distance D_1 between each of the parallel photoresist lines **116**. A pitch P_3 between centerlines C_3 of adjacent photoresist lines of the another patterned photoresist material **140** may be substantially the same as the pitch P_1 between the centerlines C_1 of the adjacent photoresist lines of the patterned photoresist material **114**. In some embodiments, the width W_3 of each of the additional parallel photoresist lines **142** is about 50 nm, the distance D_3 between adjacent additional parallel photoresist lines is about 70 nm, and the pitch P_3 between the centerlines C_3 of adjacent additional parallel photoresist lines is about 120 nm. The another patterned photoresist material **140** may be formed using conventional processes, such as those previously described in relation to forming the patterned photoresist material **114**.

Referring to next to FIG. 6, the another patterned photoresist material **140** (FIG. 5) may be used to form another patterned spacer material **146** including additional parallel spacers **148** separated by fourth trenches **150**. The another patterned spacer material **146** may define a second pattern **152** to be transferred to the intermediate template structure **128** (FIG. 4), as described in further detail below. Each of the additional parallel spacers **148** may be formed of and include a material suitable for use as a mask for selectively removing (e.g., etching) portions of the additional template masking materials **134** and the intermediate template structure **128**. The material of the additional parallel spacers **148** may be the same as or different than the material of the parallel spacers **122** of the patterned spacer material **120**, previously described with respect to FIG. 2. In some embodiments, each of the additional parallel spacers **148** is formed of and includes a silicon oxide.

The dimensions and spacing of the additional parallel spacers **148** may be selected to provide desired dimensions and spacing for features of a template structure to be formed using the another patterned spacer material **146**, as described in further detail below. The additional parallel spacers **148** may have substantially similar dimensions and spacing as the parallel spacers **122** of the patterned spacer material **120**, except oriented in a direction substantially perpendicular to that of the parallel features **130** (FIG. 4) of the intermediate template structure **128** (i.e., perpendicular to the direction of the parallel spacers **122**). For example, each of the additional parallel spacers **148** may have a width W_4 , thickness T_5 , and length (not shown) substantially the same as the width W_2 , the thickness T_3 , and the length (not shown) of the parallel spacers **122**, respectively. Accordingly, the width W_4 of each of the additional parallel spacers **148** may be within a range of from about 20 percent to about 40 percent of a target pitch between adjacent openings of the rectilinear array of openings to be formed using the template structure, such as from about 20 percent to about 30 percent of the target pitch. In further embodiments, at least one of the thickness T_5 and the length of each of the additional parallel spacers **148** may be different than at least one of the thickness T_3 and the length of the parallel spacers **122**. In addition, the additional parallel spacers **148** may be regularly spaced by a distance D_4 (i.e., equal to the width W_3 of each of the additional parallel photoresist lines **142**), that is substantially the same as the distance D_2 between each of the parallel spacers **122**. Accordingly, the distance D_4 between adjacent additional parallel spacers **148** may be within a range of from about 180 percent to about 160 percent of the target pitch between adjacent openings of the rectilinear array of openings to be formed using the template structure, such as from about 180 percent to about 170 percent of the target pitch. A pitch P_4 between centerlines C_4 of adjacent additional parallel spacers of the another patterned spacer material **146** may be substantially the same as the pitch P_2 between the centerlines C_2 of the adjacent parallel spacers of the patterned spacer material **120** (i.e., equal to about half of the pitch P_3 between centerlines C_3 of adjacent additional parallel photoresist lines of the additional parallel photoresist lines **142**). Accordingly, the pitch P_4 between adjacent additional parallel spacers of the another patterned spacer material **146** may be equal to about two times ($2\times$) the target pitch between adjacent openings of the rectilinear array of openings to be formed using the template structure.

By way of non-limiting example, if a target pitch between adjacent openings of the rectilinear array of openings to be formed is about 30 nm, the width W_4 of each of the additional parallel spacers **148** may be within a range of from about 6 nm to about 12 nm, the distance D_4 between adjacent additional parallel spacers of the another patterned spacer material **146** may be within a range of from about 54 nm and about 48 nm, and the pitch P_4 between centerlines C_4 of adjacent additional parallel spacers of the another patterned spacer material **146** may be about 60 nm. In some embodiments, the width W_4 of each of the additional parallel spacers **148** is about 10 nm, the distance D_4 between adjacent additional parallel spacers of the another patterned spacer material **146** is about 50 nm, and the pitch P_4 between adjacent parallel spacers of the another patterned spacer material **146** is about 60 nm. The another patterned spacer material **146** may be formed using processes substantially similar to those previously described with respect to forming the patterned spacer material **120**.

Referring to FIGS. 7A and 7B, the first pattern **152** defined by the another patterned spacer material **146** (FIG. 6) may be transferred or extended into the intermediate template struc-

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ture **128** (FIG. 4) to form a template structure **154**. The template structure **154** may include parallel features **130'** (described in more detail below), additional parallel features **156**, and elevated pillars **158**. The parallel features **130'** may intersect with the additional parallel features **156** to at least partially define wells **160**. The elevated pillars **158** may protrude from the locations where the parallel features **130** and the additional parallel features **156** intersect. A height H_3 of the elevated pillars **158** may be equal to the difference between a height H_4 of each of the parallel features **130** and the additional parallel features **156** and the thickness T_1 of the template material **106** (FIGS. 1 and 2). In some embodiments, the height H_3 of the elevated pillars **158** is about 40 nm.

The parallel features **130'** may be substantially similar (e.g., in terms of dimensions and spacing) to the parallel features **130** of the intermediate template structure **128** previously described with reference to FIG. 4, except that, as a result of extending the second pattern **152** into the intermediate template structure **128**, the parallel features **130'** may be formed from what used to be portions of the base **132** underlying the parallel features **130**. Thus, as shown in FIG. 7B, the parallel features **130'** of the template structure **154** may have substantially the same width W_2 , length (not numbered), and pitch P_2 as the parallel features **130** of the intermediate template structure **128** (FIG. 4).

The additional parallel features **156** may have substantially the same width W_4 , length (not shown), and pitch P_4 as each of the additional parallel spacers **148** (FIG. 6). The additional parallel features **156** may also have substantially the same dimensions and spacing as the parallel features **130'**, except oriented in a direction substantially perpendicular to that of the parallel features **130'**. For example, referring to FIG. 7B, the width W_4 of each of the additional parallel features **156** may be substantially the same as the width W_2 of each of the parallel features **130'**, the distance D_4 between adjacent additional parallel features of the additional parallel features **156** may be substantially the same as the distance D_2 between adjacent parallel features of the parallel features **130'**, and the pitch P_4 between centerlines C_4 of adjacent additional parallel features of the additional parallel features **156** may be substantially the same as the pitch P_2 between centerlines C_2 of adjacent parallel features of the parallel features **130**. Thus, the template structure **154** may include intersecting parallel features (i.e., the parallel features **130'**, and the additional parallel features **156**) defining substantially rectangular (e.g., square) wells. In addition, as illustrated in FIG. 7A, each of the additional parallel features **156** and the parallel features **130'** may have substantially the same height H_3 .

Since the parallel features **130'** and the additional parallel features **156** have substantially the same dimensions and spacing as the parallel spacers **122** and the additional parallel spacers **148**, the width W_2 of each of the parallel features **130'** and the width W_4 of each of the additional parallel features **156** may both be within a range of from about 20 percent to about 40 percent of a target pitch between adjacent openings of a rectilinear array of openings to be formed using the template structure **154**, such as from about 20 percent to about 30 percent of the target pitch. In addition the distance D_2 between each of the parallel spacers **122** and the distance D_4 between of the additional parallel spacers **148** may be within a range of from about 180 percent to about 160 percent of the target pitch between adjacent openings of the rectilinear array of openings to be formed using the template structure **154**, such as from about 180 percent to about 170 percent of the target pitch. Further, the pitch P_2 between centerlines C_2 of adjacent parallel features of the parallel features **130'** and the pitch P_4 between centerlines C_4 of adjacent additional parallel

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features of the additional parallel features **156** may both be about two times ($2\times$) the target pitch between adjacent openings of the rectilinear array of openings. Still further, the height H_3 of each of the parallel features **130'** and the additional parallel features **156** may be within a range of from about one-half ($1/2$) the target pitch between adjacent openings of the rectilinear array of openings and about three times ($3\times$) the target pitch between adjacent openings of the rectilinear array of openings, such as from about one times ($1\times$) the target pitch and about two times ($2\times$) the target pitch.

By way of non-limiting example, if a target pitch between adjacent openings of the rectilinear array of openings to be formed is about 30 nm, the width W_2 of each of the parallel features **130'** and the width W_4 of each of the additional parallel features **156** may be within a range of from about 6 nm to about 12 nm, the distance D_2 between adjacent parallel features of the parallel features **130'** and the distance D_4 between adjacent additional parallel features of the additional parallel features **156** may both be within a range of from about 54 nm and about 48 nm, the pitch P_2 between centerlines C_2 of adjacent parallel features of the parallel features **130'** and the pitch P_4 between centerlines C_4 of adjacent additional parallel features of the additional parallel features **156** may both be about 60 nm, and the height H_3 of each of the parallel features **130'** and the additional parallel features **156** may be within a range of from about 15 nm to about 90 nm. In some embodiments, the width W_2 of each of the parallel features **130'** and the width W_4 of each of the additional parallel features **156** are both about 10 nm, the distance D_2 between adjacent parallel features of the parallel features **130'** and the distance D_4 between adjacent additional parallel features of the additional parallel features **156** are both about 50 nm, the pitch P_2 between centerlines C_2 of adjacent parallel features of the parallel features **130'** and the pitch P_4 between centerlines C_4 of adjacent additional parallel features of the additional parallel features **156** are both about 60 nm, and the height H_3 of each of the parallel features **130'** and the additional parallel features **156** is about 35 nm.

As depicted in FIGS. 7A and 7B, the parallel features **130'** and the additional parallel features **156** may define sidewalls **162** of each the wells **160**, and the substrate masking material **104** may define a floor **164** of each of the wells **160**. Thus, if the parallel features **130'** and the additional parallel features **156** have substantially the same dimensions and spacing, each of the wells **160** may have substantially the same shape (e.g., substantially rectangular, such as substantially square), dimensions, and spacing. In some embodiments, each of the wells **160** has a square lateral cross-sectional shape, a lateral cross-sectional area of about 2500 nm², a height of about 35 nm, and is spaced apart from an adjacent well by about 10 nm.

Referring collectively to FIGS. 4, 6, and 7A, to form the template structure **154**, the additional parallel spacers **148** of the another patterned spacer material **146** may be used as a mask for at least one etching process (e.g., an anisotropic etching process) to remove unmasked portions (e.g., portions not underlying the additional parallel spacers **148**) of each of the additional template masking materials **134** and the intermediate template structure **128** (FIG. 4). The unmasked portions of the additional template masking materials **134** may be completely removed, and the unmasked portions of the intermediate template structure **128** may be partially removed. The etching process may, for example, uniformly remove unmasked portions of the intermediate template structure **128** to completely remove unmasked portions of the base **132** not underlying the parallel features **130** (FIG. 4) and to transfer the dimensions of the parallel features **130** into the unmasked portions of the base **132** underlying the parallel

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features **130** (e.g., to form the parallel features **130'** of the template structure **154**). In further embodiments, depending on the conditions (e.g., time, chemistries, etc.) of the etching process, the height H_1 of the parallel features **130** of the intermediate template structure **128** may be different than (e.g., larger than) the height H_3 of the parallel features **130'** of the template structure **154**. Remaining portions of the additional parallel spacers **148** and the additional template masking materials **134** may then be selectively removed relative to the template structure **154**.

Referring to FIGS. **8A** and **8B**, a neutral wetting material **166** may be formed over the substrate masking material **104** defining the floor **164** of each of the wells **160**. The neutral wetting material **166** may be a material that has exhibits equal affinity for different polymer blocks (and any corresponding homopolymers, if present) of a block copolymer material to be deposited in the wells **160**. Thus, the neutral wetting material **166** may not be preferential (e.g., selective) to any polymer block (or homopolymer, if present) of a block copolymer material. The neutral wetting material **166** may, for example, be a neutral wetting carbon material, or a neutral wetting polymer. As a non-limiting example, if the block copolymer material to be deposited in the wells **160** is PS-*b*-PMMA, the neutral wetting material **166** may be a random PS:PMMA copolymer material (P(S-*r*-MMA)), a benzocyclobutene (BCP)- or azidomethylstyrene (AMS)-functionalized random copolymer of styrene and methyl methacrylate (e.g., P(S-*r*-MMA-*r*-BCP)), a hydroxyl functionalized random copolymer of styrene and methyl methacrylate (e.g., a 2-hydroxyethyl methacrylate (HEMA) functionalized random copolymer of styrene and methyl methacrylate (P(S-*r*-MMA-*r*-HEMA))), or a neutral wetting carbon material. In some embodiments, the neutral wetting material **166** is a neutral wetting carbon material. The neutral wetting material **166** may partially fill each of the wells **160**. The neutral wetting material **166** may be formed at any suitable thickness facilitating the formation of the self-assembled block copolymer material, such as a thickness within a range of from about 5 nm to about 10 nm.

The neutral wetting material **166** may be formed using conventional processes (e.g., a PVD process, a CVD process, an ALD process, or a spin-coating process), which are not described in detail herein. By way of non-limiting example, if the neutral wetting material **166** is a neutral wetting carbon material, the neutral wetting carbon material may be deposited in the wells **160** by a CVD process. As another non-limiting example, if the neutral wetting material **166** is a neutral wetting random copolymer material, the neutral wetting random copolymer material may be spin-coated into the wells **160** and cross-linked (e.g., by way of at least one of thermal-processing and photo-processing). After forming the neutral wetting material **166** on the floor **164** of the wells **160**, portions of the neutral wetting material **166** present on surfaces of the template structure **154** (e.g., surfaces of the parallel features **130'**, the additional parallel features **156**, and the elevated pillars **158** not proximate the substrate masking material **104**) may be removed.

In additional embodiments, the neutral wetting material **166** may be formed on the substrate masking material **104** prior to forming the template structure **154**. For example, the neutral wetting material **166** may be formed between the substrate masking material **104** and the template material **106** (FIG. **1**), and then the template structure **154** may be formed as previously described with reference to FIGS. **1** through **7B** (i.e., such that the template structure **154** is formed over the neutral wetting material **166**, and such that the neutral wetting material **166** defines the floor **164** of each of the wells **160**).

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Referring next to FIGS. **9A** and **9B**, a block copolymer material **168** may be formed (e.g., deposited) in each of the wells **160**. As used herein, the term "block copolymer material" means and includes a material including at least one block copolymer. In turn, as used herein, the term "block copolymer" means and includes a polymer including two or more polymer blocks covalently bound to one or more polymer blocks of unlike type. The block copolymer material may also include at least one homopolymer of the same polymer type as a polymer block of the block copolymer included therein. As used herein, the term "homopolymer" means and include a polymer including a single type of repeat unit (e.g., a single repeating monomer). For example, the block copolymer material **168** may be a self-assembling (SA) block copolymer (e.g., an SA diblock copolymer, an SA triblock copolymer, etc.), or may be a blend of an SA block copolymer and at least one homopolymer of the same polymer type as a polymer block of the SA block copolymer. Suitable SA block copolymers may include, but are not limited to, PS-*b*-PMMA, PS-*b*-PDMS, polystyrene-block-polyvinylpyridine (PS-*b*-PVP), polystyrene-block-polyisoprene (PS-*b*-PI), polystyrene-block-polybutadiene (PS-*b*-PB), polystyrene-block-poly lactide (PS-*b*-PA), polyethyleneoxide-block-polyisoprene (PEO-*b*-PI), polyethyleneoxide-block-polybutadiene (PEO-*b*-PB), polyethyleneoxide-block-poly methylmethacrylate (PEO-*b*-PMMA), polyethyleneoxide-block-polystyrene (PEO-*b*-PS), polybutadiene-block-polyvinylpyridine (PB-*b*-PVP), polyisoprene-block-poly methylmethacrylate (PI-*b*-PMMA). In some embodiments, the block copolymer material **168** is PS-*b*-PMMA. In additional embodiments, the block copolymer material **168** is PS-*b*-PDMS.

The block copolymer material **168** may have an SA block copolymer chain length and volumetric ratio of constituent polymers (i.e., polymer blocks of the SA block copolymer, and, if present, any homopolymers) facilitating the formation of a rectangular (e.g., square) array of cylindrical domains of a first polymer within a matrix domain of a second polymer in each of the wells **160**, as described in further detail below. For example, if the block copolymer material **168** is an SA diblock copolymer, a first polymer block to be self-assembled into the cylindrical domains may constitute from about 20 percent to about 40 percent of the total volume of the SA diblock copolymer, and a second polymer block to be self-assembled into the matrix domain may constitute a remaining percentage of the total volume of the SA diblock copolymer (e.g., from about 80 percent to about 60 percent of the total volume of the SA diblock copolymer). If the block copolymer material **168** is a blend of an SA block copolymer and at least one homopolymer, the at least one homopolymer may constitute from about 0.1 percent to about 40 percent of the total volume of the blend. In some embodiments, the block copolymer material **168** is a PS-*b*-PMMA copolymer including about 30 percent by volume PS and about 70 percent by volume PMMA. In additional embodiments, the block copolymer material **168** is a PS-*b*-PDMS diblock copolymer including about 30 percent by volume PS and about 70 percent by volume PDMS.

The block copolymer material **168** may substantially fill a remaining portion of each of the wells **160** (i.e., a portion of each of the wells **160** remaining after the formation of the neutral wetting material **166** therein). The sidewalls **162** of the wells **160** may be preferential wetting to one of the polymer blocks of the block copolymer material **168**. In addition, the block copolymer material **168** may be substantially contained within the wells **160** (i.e., less than or equal to a monolayer of the block copolymer material **168** may be

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located outside of the wells **160**, such as on the surfaces of the parallel features **130'**, the additional parallel features **156**, and the elevated pillars **158** outside of the wells **160**). In some embodiments, the block copolymer material **168** has a thickness within a range of about 25 nm to about 30 nm and is substantially contained in the wells **160**.

The block copolymer material **168** may be formed in each of the wells **160** using conventional processes (e.g., spin-coating, knife-coating, etc.), which are not described in detail herein. By way of non-limiting example, the block copolymer material **168** may be deposited into each of the wells **160** by spin-coating from a dilute solution of the block copolymer material **168** in an organic solvent (e.g., dichloroethane, toluene, etc.). The deposition process may be controlled so that capillary forces pull excess of the block copolymer material **168** (e.g., block copolymer material **168** deposited outside of the wells **160**) greater than a monolayer into the wells **160**.

Referring to FIGS. **10A** and **10B**, the block copolymer material **168** (FIGS. **9A** and **9B**) may be processed (e.g., annealed) to form a self-assembled block copolymer material **170** including a rectilinear array **172** of cylindrical domains **176** of a first polymer within a matrix domain **174** of a second polymer. The first polymer may correspond to a minority polymer of the block copolymer material **168** (e.g., a polymer, including a polymer block of an SA block copolymer and any corresponding homopolymer, present in a relatively lower amount), and the second polymer may correspond to a majority polymer of the block copolymer material **168** (e.g., another polymer, including another polymer block of an SA block copolymer and any corresponding homopolymer, present in a relatively greater amount). The sidewalls **162** of the wells **160** may be preferential wetting to the majority polymer of the block copolymer material **168**. For example, if the block copolymer material **168** is an SA block copolymer (e.g., an SA diblock copolymer), the first polymer may correspond to a minority polymer block of the SA block copolymer and the second polymer may correspond to a majority polymer block of the SA block copolymer. In some embodiments, the cylindrical domains **176** are formed of and include PS, and the matrix domain **174** is formed of and includes PMMA. In additional embodiments, the cylindrical domains **176** are formed of and include PS, and the matrix domain **174** is formed of and includes PDMS.

As shown in FIG. **10B**, the rectilinear array of cylindrical domains **172** may include rows of cylindrical domains **176** of the first polymer extending in an X direction and columns of the cylindrical domains **176** of the first polymer extending in a Y direction. The X direction may be substantially perpendicular to the Y direction. Each of the cylindrical domains **176** of the first polymer may have substantially the same width W_s (i.e., diameter) and height H_s , and may be oriented perpendicular (i.e., surface normal) to the substrate **102**. In addition, within each row and each column, the cylindrical domains **176** of the first polymer may be substantially aligned and regularly spaced by a distance D_s . A pitch P_s between centers C_s of adjacent cylindrical domains (e.g., adjacent cylindrical domains of a particular row or a particular column) of the rectilinear array of cylindrical domains **172** may be substantially uniform throughout the self-assembled block copolymer material **170**.

By way of non-limiting example, the width W_s of each of the cylindrical domains **176** of the first polymer may be equal to about one-fourth ($1/4$) of the pitch (e.g., the pitch P_2 , and the pitch P_4) between centerlines (e.g., the centerlines C_2 , and the centerlines C_4) of adjacent features (e.g., adjacent parallel features of the parallel features **130'**, and adjacent additional parallel features of the additional parallel features **156**) of the

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template structure **154**. In addition, the height H_s of each of the cylindrical domains **176** of the first polymer may be equal to the height of the block copolymer material **168** (FIGS. **9A** and **9B**). Furthermore, the pitch P_s between centers C_s of adjacent cylindrical domains may be equal to about one-half ($1/2$) of the pitch (e.g., the pitch P_2 and the pitch P_4) between centerlines (e.g., the centerlines C_2 , and the centerlines P_4) of adjacent parallel features (e.g., adjacent parallel features of the parallel features **130'**, and adjacent additional parallel features of the additional parallel features **156**) of the template structure **154**. In some embodiments, the width W_s of each of the cylindrical domains **176** is about 15 nm, the height H_s of the cylindrical domains **176** is within a range of from about 25 nm to about 30 nm, and the pitch P_s between centers C_s of adjacent cylindrical domains of the cylindrical domains **176** is about 30 nm.

As illustrated in FIG. **10B**, the rectilinear array **172** of cylindrical domains **176** of the first polymer may be considered an aggregate of rectangular (e.g., square) arrays (not numbered) of the cylindrical domains **176** of the first polymer contained within the wells **160**. Namely, within each of the wells **160**, the dimensions and preferential wetting characteristics of the sidewalls **162** (i.e., as defined by parallel features **130'** and additional parallel features **156** of the template structure **154**) in combination with the characteristics of the neutral wetting material **166**, facilitates the formation of a rectangular array of the cylindrical domains **176** of the first polymer within the matrix domain **174** of the second polymer. Each rectangular array includes four of the cylindrical domains **176** of the first polymer having the dimensions and spacing previously described (e.g., width W_s , height H_s , and pitch P_s) in rectangular (e.g., square) registration. In turn, the dimensions and spacing of each of the parallel features **130'** and the additional parallel features **156** of the template structure **154** enables adjacent cylindrical domains **176** of adjacent rectangular arrays (i.e., in adjacent wells) to have the same alignment, dimensions, and spacing, resulting in the rectilinear array **172** of cylindrical domains **176**.

The self-assembled block copolymer material **170** may be formed using an annealing process. For example, the block copolymer material **168** may be thermally annealed at a temperature above the glass transition temperature of the polymer blocks and homopolymers (if any) of the block copolymer material **168** to effectuate separation and self-assembly according to the wetting characteristics of the wells **160** (e.g., the preferential wetting characteristics of the sidewalls **162**, and the neutral wetting characteristics of the neutral wetting material **166** on the floor **164**). As another example, the block copolymer material **168** may be solvent annealed by swelling the polymer blocks and homopolymers (if any) of the block copolymer material **168** with a solvent and then evaporating the solvent. In some embodiments, such as where the block copolymer material **168** is a PS-*b*-PMMA copolymer, the block copolymer material **168** is annealed at a temperature within a range of from about 180° C. to about 250° C. in a vacuum oven or under an inert atmosphere for a period of time within a range of from about 2 minutes to about 24 hours to form the self-assembled block copolymer material **170**.

Referring next to FIGS. **11A** and **11B**, the cylindrical domains **176** (FIGS. **10A** and **10B**) of the first polymer may be selectively removed to form a patterned polymer material **178** including the matrix domain **174** of the second polymer surrounding cylindrical openings **180**. The cylindrical openings **180** have substantially the same dimensions (e.g., width W_s , and height H_s), spacing (e.g., distance D_s , and pitch P_s), and alignment as the cylindrical domains **176** of the first polymer. The patterned polymer material **178** may thus define

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a rectilinear pattern **182** of cylindrical openings **180** (i.e., derived from and having substantially the same dimensions and spacing as the rectilinear array of cylindrical domains **172** of the first polymer) to be transferred to the substrate **102**, as described in further detail below.

The selective removal of the cylindrical domains **176** of the first polymer to form the patterned polymer material **178** may be performed using conventional processes, which are not described in detail herein. By way of non-limiting example, the cylindrical domains **176** of the first polymer may be removed using at least one of an oxygen plasma process and a chemical dissolution process (e.g., a process including irradiating the cylindrical domains **176** of the first polymer, ultrasonically the self-assembled block copolymer material **170** in acetic acid, ultrasonically the self-assembled block copolymer material **170** in deionized water, and rinsing the self-assembled block copolymer material **170** to remove the cylindrical domains **176** of the first polymer).

Referring next to FIGS. **12A** and **12B**, the rectilinear pattern **182** of cylindrical openings **180** defined by the patterned polymer material **178** may be transferred or extended into the substrate **102** (FIGS. **11A** and **11B**) to form a patterned substrate **184** including a rectilinear array **186** of openings **188**. The rectilinear array **186** may include rows of openings **188** extending in the X direction and columns of the openings **188** extending in the Y direction. The openings **188** may extend partially into the patterned substrate **184**, or may extend completely through the patterned substrate **184**. The openings **188** may have substantially the same width W_s as the cylindrical openings **180** of the patterned polymer material **178** (i.e., the same width W_s as the cylindrical domains **176** of the self-assembled block copolymer material **170**). In addition, within each row and each column, the openings **188** may be substantially aligned and may have the same pitch P_s as the cylindrical openings **180** of the patterned polymer material **178** (i.e., the same pitch P_s as the cylindrical domains **176** of the self-assembled block copolymer material **170**). In some embodiments, each of the openings **188** extends partially into the patterned substrate **184**, the width W_s of each of the openings **188** is about 15 nm, and the pitch P_s between adjacent openings **188** is about 30 nm.

To form the patterned substrate **184**, the matrix domain **174** of the patterned polymer material **178** may be used as a mask for at least one etching process (e.g., an anisotropic etching process, such as an reactive ion etching process) to substantially remove unmasked portions (e.g., portions not underlying the matrix domain **174**) of each of the substrate masking material **104** and the substrate **102**. The unmasked portions of the substrate masking material **104** may be completely removed, and the unmasked portions of the substrate **102** may be at least partially removed (i.e., may be partially removed, or may be completely removed). The etching process may, for example, extend the rectilinear pattern **182** of openings **180** partially through the substrate **102** to form the rectilinear array **186** of openings **188** of the patterned substrate **184**.

Accordingly, a method of forming a rectilinear array of openings in a substrate may comprise forming a template structure comprising a plurality of parallel features and a plurality of additional parallel features perpendicularly intersecting the plurality of additional parallel features of the plurality over a substrate to define wells, each of the plurality of parallel features having substantially the same dimensions and relative spacing as each of the plurality of additional parallel features. A block copolymer material may be formed in each of the wells. The block copolymer material may be processed to form a patterned polymer material defining a

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pattern of openings. The pattern of openings may be transferred to the substrate to form an array of openings in the substrate.

In addition, a method of forming a semiconductor device structure may comprise forming a template structure comprising intersecting features defining substantially rectangular wells over a substrate, each of the intersecting features having substantially the same dimensions and being preferential wetting to a polymer block of a self-assembling block copolymer. A neutral wetting material may be formed over a floor of each of the substantially rectangular wells. A block copolymer material comprising the self-assembling block copolymer may be formed over the neutral wetting material. The block copolymer material may be self-assembled to form an array of cylindrical domains of a first polymer within a matrix domain of a second polymer, the array of cylindrical domains of the first polymer exhibiting uniform pitch between substantially all adjacent cylindrical domains of the first polymer. The cylindrical domains of the first polymer may be selectively removed to define a pattern of cylindrical openings in the matrix domain of the second polymer. The pattern of cylindrical openings may be transferred to the substrate.

Following the formation of the patterned substrate **184**, remaining portions of the template structure **154** (e.g., the parallel features **130'**, the additional parallel features **156**, and the elevated pillars **158**), patterned polymer material **178** (e.g., the matrix domain **174**), and the substrate masking material **104** may be removed, as depicted in FIGS. **13A** and **13B**. These materials may be removed using conventional processes, such as conventional etching processes, which are not described in detail herein. The semiconductor device structure **100** including the patterned substrate **184** may then be subjected to additional processing, as desired. For example, the openings **188** in the substrate **102** may be at least partially filled with a material, such as a conductive material, to form contacts (e.g., bond pads). By utilizing the methods of the disclosure, the contacts may be closely packed and may have a uniform pitch between adjacent contacts.

Accordingly, a semiconductor device structure of the disclosure may comprise a substrate defining a rectilinear array of openings, each opening of the rectilinear array of openings having substantially the same width of less than or equal to about 25 nm, and adjacent openings of the rectilinear array of openings having substantially the same pitch of less than or equal to about 50 nm.

The methods of the disclosure provide an effective and reliable way to control the dimensions and spacing of the rectilinear array of openings **186** of the patterned substrate **184**. The methods facilitate simple and cost-effective formation of very small openings **188** (e.g., critical dimensions of less than or equal to about 30 nm) that are closely packed (e.g., a pitch of less than or equal to about 50 nm) and are substantially aligned in multiple directions (e.g., in the X and Y directions). The methods of the disclosure advantageously facilitate improved device performance, lower cost, increased miniaturization of components, and greater packaging density as compared to conventional methods of forming a contact array for a semiconductor device structure (e.g., a DRAM device structure).

While the disclosure is susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, the disclosure is not intended to be limited to the particular forms disclosed. Rather, the disclosure is to cover all modifications, equivalent

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lents, and alternatives falling within the scope of the disclosure as defined by the following appended claims and their legal equivalents.

What is claimed is:

1. A method of forming an array of openings in a substrate, comprising:
 - forming a template structure comprising a plurality of parallel features and a plurality of additional parallel features perpendicularly intersecting the plurality of additional parallel features over a substrate to define wells, each of the plurality of parallel features having substantially the same dimensions and relative spacing as each of the plurality of additional parallel features;
 - forming a block copolymer material in the wells;
 - processing the block copolymer material to form a patterned polymer material defining a pattern of openings; and
 - transferring the pattern of openings to the substrate to form an array of openings in the substrate.
2. The method of claim 1, wherein forming the template structure comprising a plurality of parallel features and a plurality of additional parallel features comprises forming each of the parallel features and each of the additional parallel features to have substantially the same width within a range of from about 20 percent to about 40 percent of a target pitch between adjacent openings of the array of openings.
3. The method of claim 1, wherein forming the template structure comprising a plurality of parallel features and a plurality of additional parallel features comprises:
 - forming the plurality of parallel features to exhibit a substantially uniform pitch between adjacent parallel features, the substantially uniform pitch equal to about two times a target pitch between adjacent openings of the array of openings; and
 - forming the plurality of the additional parallel features to exhibit another substantially uniform pitch between adjacent additional parallel features, the another substantially uniform pitch substantially the same as the substantially uniform pitch exhibited by the plurality of parallel features.
4. The method of claim 1, wherein forming the template structure comprising a plurality of parallel features and a plurality of additional parallel features comprises forming each of the parallel features and the additional parallel features to have substantially the same height within a range of from about one-half to about three times a target pitch between adjacent openings of the array of openings.
5. The method of claim 1, wherein forming the template structure comprising a plurality of parallel features and a plurality of additional parallel features comprises:
 - forming parallel spacers over a template material, each of the parallel spacers having substantially the same dimensions and spacing;
 - transferring a first pattern defined by the parallel spacers to the template material to form an intermediate template structure comprising initial parallel features protruding from a base;
 - forming additional parallel spacers over the intermediate template structure, the additional parallel spacers oriented in a direction substantially perpendicular to the parallel spacers and having substantially the same dimensions and spacing as the parallel spacers; and
 - transferring a second pattern defined by the additional parallel spacers to the intermediate template structure to form the template structure.
6. The method of claim 5, wherein forming parallel spacers over the template material comprises:

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- forming parallel photoresist lines exhibiting a first substantially uniform pitch between adjacent parallel photoresist lines, each of the parallel photoresist lines having substantially the same width and height;
- forming a spacer material over the parallel photoresist lines; and
- removing a portion of the spacer material to form the parallel spacers on sidewalls of the parallel photoresist lines, the parallel spacers exhibiting a second substantially uniform pitch between adjacent parallel spacers, the second substantially uniform pitch equal to about one-half the first substantially uniform pitch.
7. The method of claim 6, wherein forming additional parallel spacers over the intermediate template structure comprises:
 - removing materials remaining over the intermediate template structure after the formation thereof;
 - forming additional parallel photoresist lines over the intermediate template structure after removing materials remaining over the intermediate template structure, the additional parallel photoresist lines oriented in a direction substantially perpendicular to the parallel photoresist lines and having substantially the same dimensions and spacing as the parallel photoresist lines;
 - forming additional spacer material over the additional parallel photoresist lines; and
 - removing a portion of the additional spacer material to form the additional parallel spacers on sidewalls of the additional parallel photoresist lines.
8. The method of claim 5, wherein transferring the first pattern defined by the parallel spacers to the template material to form the intermediate template structure comprises extending the first pattern partially into the template material.
9. The method of claim 1, wherein forming the template structure comprising the plurality of parallel features and the plurality of additional parallel features comprises forming the template structure from a template material preferential wetting to a polymer block of the block copolymer material.
10. The method of claim 1, further comprising forming a neutral wetting material over floors of the wells prior to forming the block copolymer material in the wells.
11. The method of claim 1, wherein forming the block copolymer material in the wells comprises formulating the block copolymer material to have a block copolymer chain length and volumetric ratio of constituent polymers facilitating the formation of a rectangular array of cylindrical domains of a first polymer within a matrix domain of a second polymer within the wells during the processing of the block copolymer material.
12. The method of claim 1, wherein forming the block copolymer material in the wells comprises depositing a self-assembling diblock copolymer comprising:
 - a first polymer block comprising from about 20 percent to about 40 percent of a total volume of the self-assembling diblock copolymer; and
 - a second polymer block comprising a remaining percentage of the total volume of the self-assembling diblock copolymer.
13. The method of claim 1, wherein processing the block copolymer material to form a patterned polymer material defining a pattern of openings comprises:
 - annealing the block copolymer material to form a self-assembled block copolymer material comprising an array of cylindrical domains of a first polymer within a matrix domain of a second polymer; and
 - selectively removing the cylindrical domains of the first polymer to form the patterned polymer material.

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14. A method of forming a semiconductor device structure, comprising:

forming a template structure comprising intersecting features defining substantially rectangular wells over a substrate, each of the intersecting features having substantially the same dimensions and being preferential wetting to a polymer block of a self-assembling block copolymer;

forming a neutral wetting material over a floor of each of the substantially rectangular wells;

forming a block copolymer material comprising the self-assembling block copolymer over the neutral wetting material;

self-assembling the block copolymer material to form an array of cylindrical domains of a first polymer within a matrix domain of a second polymer, the array of cylindrical domains of the first polymer exhibiting uniform pitch between substantially all adjacent cylindrical domains of the first polymer;

selectively removing the cylindrical domains of the first polymer to define a pattern of cylindrical openings in the matrix domain of the second polymer; and transferring the pattern of cylindrical openings to the substrate.

15. The method of claim 14, wherein forming the template structure comprising intersecting features defining substantially rectangular wells comprises forming the intersecting features to have the same width within a range of from about 6 nm to about 12 nm.

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16. The method of claim 14, wherein forming the template structure comprising intersecting features defining substantially rectangular wells comprises forming the intersecting features to exhibit a substantially uniform pitch of less than or equal to about 60 nm between adjacent parallel features thereof.

17. The method of claim 14, wherein the self-assembling block copolymer comprises PS-b-PMMA or PS-b-PDMS.

18. The method of claim 14, wherein forming the block copolymer material comprising the self-assembling block copolymer over the neutral wetting material comprises depositing the block copolymer material to substantially fill a remaining space within each of the substantially rectangular wells.

19. The method of claim 14, wherein self-assembling the block copolymer material to form an array of cylindrical domains of a first polymer within a matrix domain of a second polymer comprises annealing the block copolymer material to form an array of four of the cylindrical domains of the first polymer within the matrix domain of the second polymer in each of the substantially rectangular wells.

20. The method of claim 14, wherein transferring the pattern of cylindrical openings to the substrate comprises etching the substrate using the matrix domain of the second polymer as an etch mask to form an array of openings in the substrate.

21. The method of claim 20, further comprising at least partially filling the array of openings with material.

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